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Vortex dynamics and melting in niobium

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Abstract

Small angle neutron scattering has been used to investigate the vortex scattering in a single crystal of niobium. Below the irreversibility line resolution-limited Bragg peaks are observed, indicating that a crystalline vortex lattice with long range order exists. Above the irreversibility line intrinsic transverse widths develop, while close to H_{c2} intrinsic radial widths also develop. Nevertheless the basic six-fold symmetry of scattering is observed throughout the vortex phase, indicating that a correlated flux fluid exists in the reversible regime.

A central problem concerning the dynamics of vortices in superconductors is whether or not they undergo a melting transition from a lattice or glass at low temperatures and fields to a liquid phase at higher T and H. Early work in the cuprate systems identified an irreversibility line [1], suggesting that the basic vortex behavior was quite different than for conventional superconductors [2]. This melting behavior was thought to originate from the unique physical properties of the cuprates, namely the large κ, intrinsic anisotropy, and high thermal energies available near T_c, but a reexamination of conventional superconductors has revealed that they also undergo a melting phenomenon [3–5]. We have therefore been carrying out an extensive series of small angle neutron scattering measurements on a high quality single crystal of niobium to investigate this question. We observe a broadening of the vortex peaks, first in the vicinity of the irreversibility line, and then again close to H_{c2}. The basic six-fold symmetry of the scattering, however, is preserved throughout the vortex regime, indicating that a correlated flux fluid exists rather than a conventional isotropic fluid.

The experiments were carried out on the NG-3 and NG-7 30 m small angle neutron scattering (SANS) spectrometers in the Cold Neutron Research Facility at NIST. The sample was a high purity single crystal of Nb in the form of a cylinder 1.25 cm in diameter and 9 cm long, with the [110] crystallographic axis along the cylinder axis. The field was applied approximately parallel to the incoming/exiting neutrons, and perpendicular to the cylinder axis. The beam diameter was typically 1 cm, illuminating the center portion of the crystal. Additional experimental details are given elsewhere [6].

The temperature dependence of the intrinsic Q widths of the magnetic vortex peaks is shown in Fig. 1, obtained by cooling in an applied field of 2000 Oe. Above a threshold temperature intrinsic transverse widths develop, while no intrinsic radial width can be detected. The onset of this transverse broadening is very close to where we observe this crossover from irreversible to reversible behavior in this sample, and thus we associate this broadening with the irreversible line and melting identified in bulk measurements. We have found that the scattering still has six-fold symmetry, while an isotropic vortex liquid would exhibit a ring of uniform intensity instead of peaks. We observe no intrinsic radial width in this temperature regime. We see from Fig. 1 that an intrinsic radial width is only

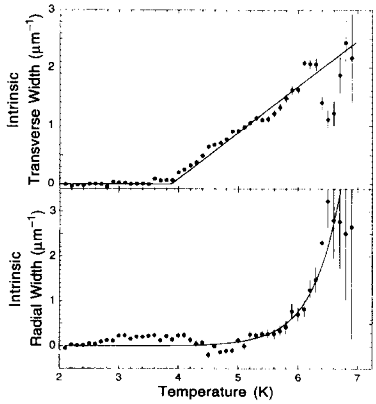

Fig. 1. Intrinsic radial and transverse (angular) widths as a function of temperature for an applied field of 2000 Oe. There is no observable intrinsic width at low T. The solid curves are a guide to the eye.

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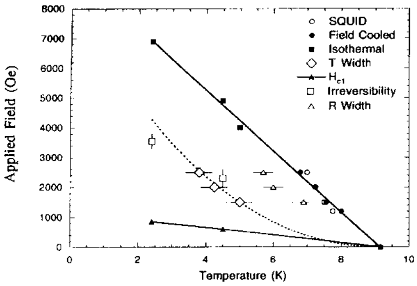

Fig. 2. Phase diagram determined for Nb (see text).

observed close to T_c, but even here the six-fold symmetry is still preserved. Indeed we find no evidence of an isotropic liquid ring of scattering under any conditions.

The phase diagram we have determined is shown in Fig. 2. The H_{c2} phase boundary is determined by three separate sets of measurements. The open circles are SQUID measurements taken on a small piece cut from the end of the crystal, with H_{c2} defined as the onset of bulk diamagnetism. The solid circles are obtained from our $I(T)$ data, while the solid squares are determined by the field where the isothermal scattering vanishes. Good agreement is obtained between these data, demonstrating that within our experimental sensitivity the vortex scattering disappears at H_{c2}. We also show the field where the flux begins to penetrate the sample, which is identified as the sudden onset of vortex scattering as H increases beyond $\frac{1}{2}H_{c1}$, where the $\frac{1}{2}$ comes from the demagnetization factor for our sample geometry. In the local limit we estimate $\kappa \approx (H_{c2}/H_{c1})^{1/2} \approx 2$. This is considerably above the value of $\kappa \approx 0.8$ obtained in very high purity/defect free Nb [7], but considerably smaller than κ obtained on sputtered films [5] (≈ 10), or cold-rolled foils [4] (~ 7), where melting curves have been identified.

The irreversibility line (open squares) as determined by our isothermal measurements, the onset temperature of the intrinsic transverse widths (open diamonds), and the onset of the radial widths (open triangles), are also shown in Fig. 2. It is clear that the irreversibility line and transverse Q broadening occur in close proximity to each other, and well below H_{c2}. We note that our irreversibility curve is substantially below that of Drulis et al. [4] obtained on the higher κ cold-rolled foils, and their curve is below that found by Schmidt et al. for high-κ sputtered films [5], supporting the expectation that T_{irr} depends on the defect/pinning strength/density in the material.

The temperature dependence of the widths of the vortex peaks must originate from the vortex dynamics, and there are two alternative explanations for our data. The first is that the development of the transverse widths, coupled with the irreversibility line we observe, signals a transition to an orientationally disordered or hexatic vortex phase. At a higher temperature the development of intrinsic radial widths indicates that translational symmetry is also lost. The implication is that there are three vortex regimes: a crystalline phase at low T, an orientationally disordered phase at intermediate T, and a correlated flux fluid in the high-T regime.

A second possible interpretation is that the transverse width originates from strong inelastic scattering associated with the soft shear mode of the vortex lattice – the same mode that would be involved in melting. Thus with sufficiently high resolution the elastic and inelastic scattering could be distinguished; one would have to assume that these are convolved into a single broadened peak given the present resolution. This interpretation implies that the lattice has not yet melted with the onset of transverse broadening, in which case the observed irreversibility curve would not be associated with melting. The melting would instead be identified with a transition to a fluid phase where the radial widths increase.

We favor the first intrepretation based on the abrupt onset of the transverse widths coupled with our own irreversibility data. However, in either scenario we have found that the basic six-fold symmetry is preserved throughout. If this vortex correlation originates from the underlying crystal anisotropy, then an isotropic liquid would only be observed if the crystalline anisotropy were negligible. In all other cases a correlated flux liquid is realized.

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